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Experimental demonstration of the intracavity excitation of TE-guided modes

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Abstract: The excitation of TE-guided modes in a planar waveguide by the intracavity radiation of a He-Ne laser was experimentally demonstrated. The excitation was performed using a new type of coupling prism of double internal reflection with the input-output faces inclined under the Brewster angle with respect to the intracavity radiation so as to reduce the intracavity reflection losses introduced by the coupling prism. Intracavity reflectance spectra were obtained.

1. Introduction

The waveguide spectroscopy of thin films [1] is a branch of integrated optics which develops techniques of investigating the optical parameters [2–4] of waveguide structures. These techniques employ prism couplers [5–7] consisting of a triangular coupling prism the base of which is in optical contact with a planar waveguide. The excitation of guided modes in a waveguide occurs due to the phenomenon of frustrated internal reflection when part of the light energy of being reflected light leaks or tunnels through the air gap (so-called photonic barrier) [8] between the prism base and the waveguide. This optical tunneling can be observed only when the condition of equality of the guided mode phase velocity and the component of the phase velocity of reflected light in the direction of the mode propagation is satisfied. Recording the energy angular distribution of the light reflected on the interface between the prism and waveguide shows intensity dips. Their angles of observation are equal to the excitation angles of guided modes when phase synchronization occurs i.e. in the reflected light so-called black m-lines [9] are observed. The m-line being a resonance effect, its angular width increases with the waveguide absorption losses. Also, the dependence of the light reflectance on the incidence angle allows one to restore not only optical properties of waveguides, but their optical structures. Nevertheless, accurate measuring low optical losses of waveguides is affected by the influence of the coupling prism. Decreasing the gap width between the prism and the waveguide increases the coupling efficiency [10] and, as a consequence, the reflectance spectra contrast. But the data obtained are strongly influenced by the refractive index and attenuation coefficient of the prism. This fact should be taken into account when calculating the parameters of the waveguide. This, in turn, complicates the problem of finding the parameters of the waveguide under investigation. Conversely, increasing the gap between the prism and the waveguide decreases the coupling efficiency. Thus, the reflectance spectra obtained in this case can not provide reliable data for exact calculations. Resolving this dilemma demands applying techniques more sensitive to the optical losses such as the methods of intracavity laser spectroscopy [11,12]. In these techniques it is the intracavity radiation of lasers that interacts with the optical sample under study. The result of such interactions depends not only on the optical absorptivity of the sample, but on the laser gain. The lower the gain, the stronger the reaction of the intracavity laser radiation on the insertion loss. That's why the techniques of intracavity laser spectroscopy demonstrate high sensitivity, especially in the case of low gain lasers. To apply the intracavity laser techniques for investigating a waveguide structure means to realize interaction of the intracavity radiation with the waveguide structure. For observing the result of this interaction, the excitation of guided modes, two problems should be solved. The first problem is the reflection losses on the

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input-output faces of the coupling prism. Such losses can be significantly greater than the gain of the laser cavity and that, in turn, may not allow the laser to radiate. The second problem is to keep the laser cavity aligned when rotating the prism to record reflectance spectra. A method of intracavity excitation of TM-guided modes with a Brewster prism coupler [13] in the cavity of a He-Ne laser was presented in [14]. In the proposed prism the first problem was solved by designing the coupling prism in such a way that the intracavity radiation fall on the input face of the prism under the Brewster angle. For this reason this type of coupling prism can be used in classical layouts to excite only the TM-guided modes. The second problem was solved by using not a triangular coupling prism, but in the form of a parallelepiped. In this type of prism the intracavity radiation undergoes not single, as usually, but double internal reflection to keep the intracavity radiation on both sides of the coupler parallel to each other.

2. Intracavity prism coupler

In this Article, we report on the intracavity excitation of TE-guided modes by means of a specially elaborated coupling prism. Because in the theory the reflection losses can be reduced to zero only for TM-polarised radiation, the classical configuration of prism couplers [5] doesn't make it possible to excite TE-guided modes by the intracavity laser technique. To excite TE-guided modes by this technique a new type of prism coupler was elaborated. More specifically, we manufactured a coupling prism in which the intracavity radiation is TM-polarized when refracting on the input-output faces of the given prism and TE-polarized when reflecting on the prism bases. Since the intracavity radiation is a superposition of rays propagating in opposite directions, the refracting faces of the prism are input and output ones at the same time. Hence, the name input-output faces. The intracavity prism coupler design for excitation of TE-guided modes is shown in Fig. 1. Here, the intracavity radiation 1 falls on the first input-output face 2 of the prism 3 under the Brewster angle i_B, refracts on it at point A. In this point the intracavity radiation is TM-polarized with respect to the refraction surface. Then it falls on the prism base contacting with the planar waveguide 4 at point B. After a total internal reflection (or, if the mode synchronization is achieved, frustrated one) the intracavity radiation falls on the opposite base of the prism, undergoes total internal reflection at point C and refracts again at point D under the Brewster angle i_B. In this configuration the second internal reflection restores the initial direction of propagation of the light. Therefore, the intracavity beams 1 and 5 remain parallel to each other on both sides of the prism coupler despite the rotation of the prism.

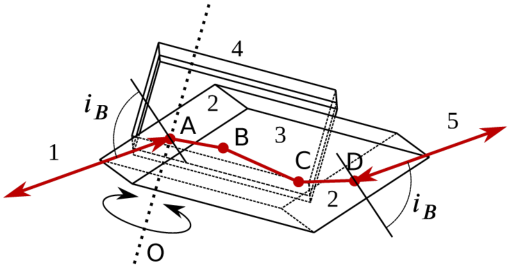

Fig. 1. Prism coupler for the intracavity excitation of TE-guided modes.

As a planar waveguide, we used a five modes ion-exchanged waveguide [15] on K8 optical glass [16]. The effective indices of refraction of the corresponding TE-guided modes were measured with a goniometer by the well-known prism-coupling technique [2,17,18]. Their values were found to be equal to $n_0 = 1.531$, $n_1 = 1.525$, $n_2 = 1.520$, $n_3 = 1.514$, and $n_4 = 1.510$. On the basis of these preliminary obtained data the coupling prism was designed. In this prism the minimum reflection losses on the input-output faces of the prism correspond to the excitation angle of a guided mode with effective index of refraction approximately equal to 1.52. When choosing optical glass for producing a prism, we should take into account that the refraction index of prism material must be higher than the effective index of refraction of the guided mode to be excited. It means that to be able to excite all the modes in our waveguide, optical glass with refraction index higher than $n = 1.54$ was required. Also, the absorption losses of the prism glass should be as low as possible so as to maintain the intracavity losses at the minimum value. For this reason, the coupling prism was made of extra heavy crown glass (STK3). The internal transmittance of this glass was higher than 0.987 per 25 mm at the wavelength of the laser operating mode ($\lambda = 632.8$ nm). The index of refraction of the glass was equal to 1.657. Taking into account the fact that due to the rotation of the prism the incidence angle of the intracavity radiation may differ from the Brewster one, the range of the waveguide modes, that can be registered by a particular prism coupler, is limited and determined by the laser gain, the index of refraction, and absorption of the prism medium. It means that the coupling prism should be chosen or manufactured in accordance with the waveguide refractive index of the mode to be tested. In our case, the distance between the prism bases (prism height) was equal to 4.0 mm and the distance between the input-output planes was equal to 14.5 mm.

3. Experiment

In Fig. 2 the optical layout of the experimental set-up for intracavity registering TE-guide modes is shown. This set-up is a combination of intracavity prism coupler 1, tilted motorized rotation 2 and translation 3 stages, photodetector 4, and elements of a He-Ne laser: mirrors 5 and 6, and discharge tube 7. In order to reduce the intracavity losses, both mirrors were high reflecting spherical ones with radii of 1.0 m. The transmittance of the mirrors was less than 0.05 % that was enough to control the intensity of the intracavity radiation by means of the photodetector. The distance between the mirrors was equal to 0.75 m which provided satisfactory stability of the cavity. The prism coupler was placed between the gain medium (discharge tube) and the mirror 5. The Brewster windows of the gas discharge tube were oriented so as to keep the intracavity radiation TE-polarized. To compensate the parallel shift of the intracavity radiation between the prism coupler and the output coupler, the last was mounted on the motorized translation stage moving in accordance with new positions of the intracavity radiation exiting from the prism coupler. The translation stage was inclined so as to compensate both horizontal and vertical lateral motions of the intracavity radiation between the prism and the coupler. The angular displacement of the prism coupler was realised by the motorized rotation stage on which the prism coupler was mounted. The axis of rotation of the stage was passing through the point of incidence of the intracavity radiation on one of the Brewster faces of the prism. As any intracavity element, the intracavity prism coupler is a source of introduced optical losses: reflection (or Fresnel) losses, absorption losses in the prism material, and the losses due to the leakage of the intracavity radiation into the waveguide in the case of phase synchronization of the reflected light component along the prism base and the corresponding guided mode. Rotating the prism about the axis O allows one to change the incidence angle of the intracavity radiation on the prism base to tune on the corresponding mode. As a result, recording the intensity of the output radiation must demonstrate radiation power output dips near the angles of excitation of guided modes. Thus, the described above intensity dips can serve as an evidence of the excitation of guided modes.

The experimental results are shown in Fig. 3. On the x-axis the angular position of the coupling prism with respect to the position of minimum reflection is represented. On the y-axis the intensity of output radiation, which is proportional to the intensity of intracavity radiation, is shown. It can be seen that the intensity of the intracavity radiation decreases as the angular distance from the zero position grows. This decrease of intensity is caused by the increase of reflection loss. At the some angular positions of the prism coupler the general sum of intracavity

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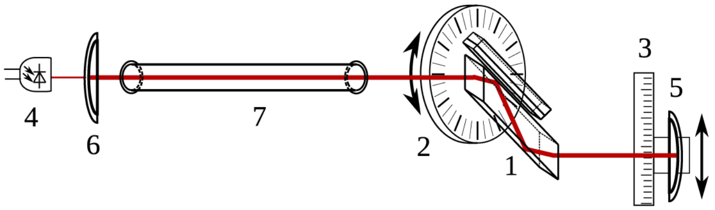

Fig. 2. Optical layout of the experimental set-up.

losses becomes greater than the laser active medium gain and the generation of intracavity radiation stops. Five intensity dips are observed on the plot. They are the result of the intracavity light energy leakage into the waveguide to excite corresponding TE-guided modes. Also, as in the case of "extra"-cavity excitation with a triangular prism [9], output of the light energy from both of the ends of the waveguide was observed. Placing a plane output coupler with a lens between the discharge tube and the coupler made possible obtaining "extra"-cavity radiation to illuminate the prism coupler. This allowed one to compare the "extra"- and intracavity techniques. The obtained results showed that in the case of intracavity configuration the excitation of guide modes may occur even at the weak coupling [19,20] of the waveguide and coupling prism.

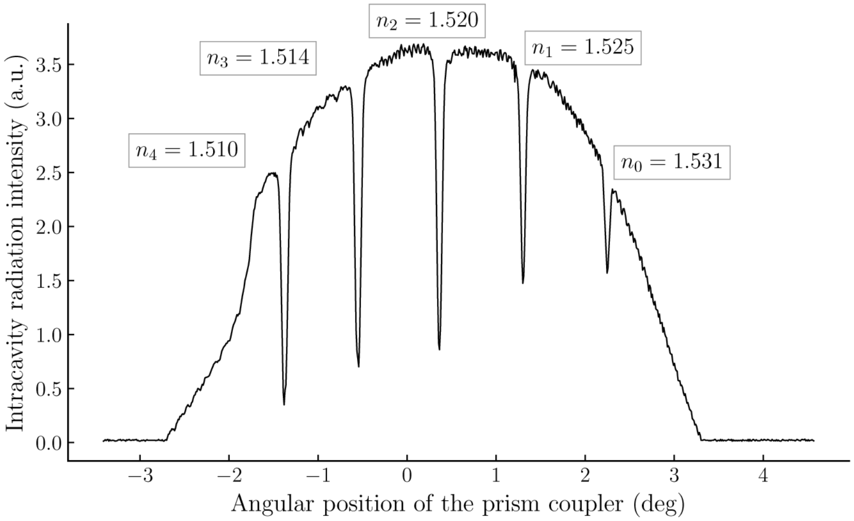

Fig. 3. Intensity of intracavity radiation vs. angular position of the coupling prism.

4. Conclusion

The tunneling and confining light energy of the intracavity radiation in TE-guided modes with a special type of prism coupler was demonstrated experimentally. The intracavity reflection spectra in the case of excitation of TE-guided modes were obtained. The elaborated technique may be used for increasing sensitivity of prism coupler sensors [21]. Since the reflectance of the intracavity radiation depends on the "prism coupler-waveguide" gap width, at some pressure of the waveguide to the coupling prism the light energy leakage into the wavegude may suppress one or several laser cavity modes. This allows one to use an intracavity prism coupler as a source of controllable intracavity losses [14,22].

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper may be obtained from the authors upon reasonable request.

References

1. A. Khomchenko, *Waveguide Spectroscopy of Thin Films*, Volume 33, Thin Films and Nanostructures (Academic Press, 2005).
2. R. Ulrich and R. Torge, "Measurement of thin film parameters with a prism coupler," Appl. Opt. **12**(12), 2901–2908 (1973).
3. A. V. Khomchenko, A. B. Sotsky, A. A. Romanenko, E. V. Glazunov, and A. V. Shulga, "Waveguide technique for measuring thin film parameters," Tech. Phys. **50**(6), 771–779 (2005).
4. S. T. Kirsch, "Determining the refractive index and thickness of thin films from prism coupler measurements," Appl. Opt. **20**(12), 2085–2089 (1981).
5. J. Seligson, "Prism couplers in guided-wave optics: design considerations," Appl. Opt. **26**(13), 2609–2611 (1987).
6. K. S. Chiang, S. Y. Cheng, and Q. Liu, "Characterization of ultrathin dielectric films with the prism-coupler method," J. Lightwave Technol. **25**(5), 1206–1212 (2007).
7. V. I. Sokolov, N. V. Marusin, V. Y. Panchenko, A. G. Savelyev, V. N. Seminogov, and E. V. Khaydukov, "Determination of refractive index, extinction coefficient and thickness of thin films by the method of waveguide mode excitation," Quantum Electron. **43**(12), 1149–1153 (2013).
8. A. B. Shvartsburg, "Tunneling of electromagnetic waves: paradoxes and prospects," Phys.-Usp. **50**(1), 37–51 (2007).
9. G. A. Teh and G. I. Stegeman, "Symmetrical prism as input coupler for integrated optics," Appl. Opt. **17**(20), 3191–3192 (1978).
10. P. S. Chung, "Ray-optical analysis of the prism-film coupling efficiency in optical waveguides," J. Phys. D: Appl. Phys. **9**(6), 887–902 (1976).
11. V. M. Baev, T. Latz, and P. E. Toschek, "Laser intracavity absorption spectroscopy," Appl. Phys. B **69**(3), 171–202 (1999).
12. H. Kimble, "Calculated enhancement for intracavity spectroscopy with a single-mode laser," IEEE J. Quantum Electron. **16**(4), 455–461 (1980).
13. A. Shulga, "Brewster prism coupler for the intracavity excitation of tm guided modes," Appl. Opt. **59**(13), 3992–3994 (2020).
14. A. V. Shulga, A. V. Khomchenko, and I. V. Shilova, "Intracavity waveguide spectroscopy of thin films," Tech. Phys. Lett. **44**(11), 953–955 (2018).
15. S. Yliniemi, B. R. West, and S. Honkanen, "Ion-exchanged glass waveguides with low birefringence for a broad range of waveguide widths," Appl. Opt. **44**(16), 3358–3363 (2005).
16. A. A. Podvyaznyi and D. V. Svistunov, "Ion-exchange waveguides formed in glasses using silver-containing melts," Tech. Phys. Lett. **29**(6), 456–458 (2003).
17. S. Monneret, P. Huguet-Chantôme, and F. Flory, "m-lines technique: prism coupling measurement and discussion of accuracy for homogeneous waveguides," J. Opt. A: Pure Appl. Opt. **2**(3), 188–195 (2000).
18. A. V. Khomchenko, A. B. Sotsky, A. A. Romanenko, E. V. Glazunov, and D. N. Kostyuchenko, "Determining thin film parameters by prism coupling technique," Tech. Phys. Lett. **28**(6), 467–470 (2002).
19. R. Ulrich, "Theory of the prism–film coupler by plane-wave analysis," J. Opt. Soc. Am. **60**(10), 1337–1350 (1970).
20. V. I. Sokolov, N. V. Marusin, S. I. Molchanova, A. G. Savelyev, E. V. Khaydukov, and V. Y. Panchenko, "Reflection of a TE-polarised gaussian beam from a layered structure under conditions of resonance excitation of waveguide modes," Quantum Electron. **44**(11), 1048–1054 (2014).
21. A. B. Sotsky, I. U. Primak, A. V. Khomchenko, and A. V. Tomov, "Sensitivity of integrated optical sensors based on a prism coupler," Opt. Quantum Electron. **31**(2), 191–200 (1999).
22. A. Shulga, "Generation of radially polarized beams by intracavity waveguide technique," in *2019 IEEE 8th International Conference on Advanced Optoelectronics and Lasers (CAOL)*, (2019), pp. 170–173.